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COMPOSITE REPAIR OF CRACKED ALUMINUM ALLOY AIRCRAFT STRUCTURE

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Structural Concepts Branch
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Structures Division

September 1987

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This technical report has been reviewed and is approved for publication.

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A bonded composite patch repair of fatique-cracked aluminum on aircraft has advantages over a standard bolted metal patch repair, such as no severe stress concentrations (no bolt holes), fatigue-resistant patch, thinner patch, simple molding techniques, a sealed interface to help prevent corrosion, and usually no inspection (NDI) problems. The objective of this program was to determine the effect of composite patches on stress intensity and crack growth characteristics of aluminum. This was accomplished by studying metal thickness and patch parameters (area, thickness, and ply orientation) effects on crack growth rate of the composite patch/aluminum specimen. Both room temperature and elevated temperature (250°F) curing adhesives were studied. The testing procedure consists of edge cracking a 4-inch x 18-inch 2024-T3 aluminum specimen to a length of between 0.3 and 0.5 inch. The aluminum is then prepared for bonding, normally using the phosphoric acid non-tank anodize (PANTA) method, primed, and patched. The specimen

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then cycled to failure. Both constant amplitude and flight spectrum loading were used. Patch material for most specimens was 5521/4 boron/epoxy. Results have shown thickness of the metal being repaired to be the most significant factor in the repair process. There was also a significant difference in results between constant amplitude and spectrum tests. Comparisons between unpatched specimens with a 0.5-inch crack and high-temperature cured, patched specimens with 0.5-inch cracks showed 1/16-inch thick aluminum constant amplitude-loaded (R=0.1, maximum stress=20 KSI) specimens to have lifetime extensions of greater than 25 times. 1/8-inch thick aluminum constant amplitude tests showed lifetime extensions of about 15 times, while 1/16-inch thick and 1/8-inch thick spectrum loaded specimens showed extensions of about 15 and 7 times, respectively.

FOREWORD

This work was performed as a joint effort between the Fatigue, Fracture, and Reliability Group, Structural Integrity Branch and the Structural Concepts Evaluation Group, Structural Concepts Branch of the Structures Division, Flight Dynamics Laboratory of the Air Force Wright Aeronautical Laboratories. The work was performed as a result of a cooperative effort proposed by The Technical Cooperation Program (TTCP) technical panel PTP4 on repair. The work was performed under Project 2401, "Flight Vehicle Structures and Dynamics Technology," Work Unit 24010109, "Life Analysis Methods," from October 1981 through April 1984.

Special thanks are given to Deborah Oliveira of Beta Industries for her help in etching of specimens and constituent data analysis. Thanks is also given to Harold Stalnaker for his aid in the testing of the specimens.

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SECTION I

INTRODUCTION

In general, conventional repair procedures are often time-consuming and structurally inefficient. An improved repair method will increase availability of service equipment and reduce maintenance costs. A standard repair of cracked aluminum utilizes a metal patch bolted to the structure. The repair method studied in this program is different from the standard repair in two ways. First, the patch is made of composite material instead of aluminum. Second, the patch is adhesively bonded rather than bolted to the cracked structure.

There are several possible advantages of an adhesively bonded, composite patch over a bolted, metal patch. First of all, there are no severe stress concentrations created with the bonded method since bolt holes are not drilled in the cracked structure as they are with the bolted patch. Secondly, the boron/epoxy patch itself is a stiffer, more fatigue-resistant patch than its aluminum counterpart. The composite patch is also thinner than the aluminum patch which can be especially valuable to the aerodynamics of the aircraft with exterior patches. The composite patch is also easier to mold to curved irregular surfaces. This is because the patch can be applied in its precured state, as several layers of prepreg, and molded by hand to the shape of the component to be repaired. Another advantage is that a composite patch can be "seen through" with current non-destructive inspection (NDI) methods, such as C-scan to monitor the crack growth of the structure. Lastly, the bond which adheres the two materials also creates a sealed interface to help prevent corrosion. [1] The Australians have used this method on operational aircraft including repair of stress corrosion cracks initiating from rivet holes in Lockheed C-130 aircraft wing-plank ribs and fatigue cracks in magnesium alloy landing wheels. [1]

The project documented in this report was initiated by a request from the Australian Aeronautical Research Laboratory to conduct a TTCP (The Technical Cooperation Program) round-robin technical interchange studying the application of advanced fiber composite patches to fatigue-cracked aluminum alloy specimens. The objective of this program was to determine the effect of composite patches on stress intensity and crack growth characteristics of cracked aluminum. This was accomplished by studying metal thickness and patch parameter (area, thickness, and ply orientation) effects on stress distribution and crack growth rate of the composite patch aluminum specimen. Both room temperature and elevated temperature (250°F) curing adhesives have been studied.

SECTION II

ADHESIVE EVALUATION

The most critical part of the repair method is the adhesive. It must transfer part of the load to the composite patch and hold up under many load cycles. The adhesive should also resist moisture and other environmental effects. Another desirable property of an adhesive is a low or room temperature curing cycle. Typical structural adhesives require curing temperatures of 250°F and up. An advantage of the high temperature curing adhesive is the ease of application as far as getting the right amount of adhesive for the repair. Getting a thin, even distribution of the two part adhesives was difficult. The high-temperature curing adhesives come in a roll with the adhesive on a carrier cloth. Cutting off a piece the size of the bonded area is all that is required to get the correct amount and distribution of adhesive. There are two reasons why a room temperature curing adhesive would be more desirable for this application. First, the patch will be easier to apply with a low-temperature curing adhesive. If the adhesive needs to be heated up to 250°F, heating blankets or some other heat source will be required to bring the material to temperature. This could be troublesome, particularly for anything other than a depot-level repair. This type of heating may also require a significant amount of power if the repair is being made on the aircraft with the entire metal structure acting as a heat sink. The second reason for favoring a lower temperature curing adhesive is the differences in coefficients of thermal expansion between aluminum and composite materials. Aluminum has a coefficient of thermal expansion much higher than most composite materials. When the aluminum, adhesive, and composite patch system are brought up to temperature, the aluminum will have expanded much more than the composite patch. After the cure time, the system is cooled to room temperature. Now the aluminum and composite are coupled as one structure owing to the bond. This causes the specimen to warp, inducing bending stresses into the structure.

Three adhesives were chosen for initial single-lap shear tests to determine the relative merits of each. AF163 was chosen as the high-temperature (250°F) adhesive because it was being used in-house on other programs and was readily available. The adhesive used contained a carrier cloth. Two room temperature cure adhesives were also acquired from 3M to apply precured patches at room temperature. The first, 2216, is an off-the-shelf adhesive, while 1XB-3525 is an experimental two-part adhesive. Table 1 shows some trends of these adhesives. The 2216 gave reasonable results with both adherends made of epoxy. However, 2216 bonded to aluminum had half or less than half of the shear strength with epoxy/epoxy adherends. The 1XB-3525, however, shows a much less significant drop between epoxy-bonded and aluminum-bonded specimens. Results for 1XB-3525 are close to that of AF163. Considering the two specimens each for AF163 and 1XB-3525, each having one adherend of aluminum and one adherend of epoxy, results show an average shear strength of AF163 to be 3793 pounds and 1XB-3525 to be 3590 pounds, a 5.3% decrease in shear strength. Although these appear to be very good results for a

room temperature cure adhesive, the performance of the repaired specimens using 1XB-3525 was not acceptable in most cases. Precured patches bonded on with these adhesives failed adhesively at less than test load. The reasons for this were not established and should be studied in further work. Work with these adhesives was then dropped from the program. As a part of the program the Australians had good success using K138 room temperature cure adhesives with simple acid cleaning and an oven dry of the surfaces. This adhesive and cleaning was adopted for the room temperature phase of this program.

TABLE 1

TEST MATRIX

ADHESIVE EVALUATION

Adhesive	Top Adherend	Bottom Adherend	Etch	Sand	Co-Cure	Average Shear (lbs/in^2) Non Moisture Conditioned	Average Shear (lbs/in^2) 1% Moisture Conditioned	Percent Reduction
1. 1XB-3525	Epoxy	Epoxy	No	240 Grit	No	4680	1347	71
2. 1XB-3525	Epoxy	Epoxy	No	110 Grit	No	4330	1105	74
3. 2216	Epoxy	Epoxy	No	240 Grit	No	3145	1685	46
4. 2216	Epoxy	Epoxy	No	110 Grit	No	3060	1338	56
5. 1XB-3525	Epoxy	Aluminum	Yes	240 Grit	No	3350	2817	16
6. 1XB-3525	Epoxy	Aluminum	Yes	110 Grit	No	3830	3240	15
7. AF-163	Epoxy	Aluminum	Yes	None	Yes	4105	3655	11
8. AF-163	Epoxy	Aluminum	Yes	None	Yes	3480	3512	-1
9. 2216	Epoxy	Aluminum	Yes	240 Grit	No	1645	1415	14
10. 2216	Epoxy	Aluminum	Yes	110 Grit	No	1305	695	46
11. 1XB-3525	Aluminum	Aluminum	Yes	None	No	3440	2193	38
12.* 2216	Epoxy	Aluminum	No	240 Grit	No	-	-	-

12* - FAILED ADHESIVE WHILE HANDLING

Moisture conditioned graphite/epoxy laminates were exposed to 95% RH, $150^{O}F$ for 6 weeks to achieve 1% moisture gain by weight, prior to bonding.

SECTION III

SPECIMEN FABRICATION

The 1/16-inch and 1/8-inch specimens were constructed with 2024-T3 aluminum and the 1/4-inch specimens were constructed with 2024-T351 aluminum. Specimens were cut to 3 7/8 inch by 18 inch. Width of the specimens was limited to a maximum of 4 inches, owing to the width of the test grips. Edge cracks in the specimens were grown from 0.050-inch notches made by a band saw blade. After notching, the specimen was cycled with the same type of loading it would see after being repaired in order to initiate a crack. The crack length was measured periodically, and cycling was stopped when the crack grew to approximately 0.3 inch (a/w = 0.08, with 'a' being the length of the crack and 'w' being the width of the specimen). Both graphite/epoxy and boron/epoxy were considered for use in this program. For this application graphite/epoxy offers three advantages. First, graphite/epoxy is less expensive and more widely used in the aerospace industry than boron/epoxy. Second, graphite fibers are easier to handle (less likely to cause skin punctures) than boron fibers. Third, graphite fibers can be formed into smaller radii of curvature than boron fibers. This allows a patch to be more easily formed to odd shapes. There are also three advantages of boron/epoxy over graphite/epoxy. First, boron is stiffer than graphite and should make a more fatigue-resistant patch. Second, boron has a coefficient of thermal expansion an order of magnitude higher than graphite. This helps keep the problem of induced stresses due to warping at high cure temperatures to a minimum. Third, boron in contact with aluminum does not cause the galvanic response as graphite does. Graphite/epoxy patches would require a layer of noncorrosive material at the aluminum surface which would require the depot to store an additional repair material. Considering the trade-offs between these two materials, the boron/epoxy was chosen. The additional cost of the boron does not carry too much importance because of the small amount of material being used. The personnel hazard of possible puncture wounds can be minimized with proper care. The smaller radius of curvature would be important in some cases, but the added stiffness, combined with the reduced problems of induced stresses and corrosion, outweigh the benefits of graphite.

Figure 1 is a drawing of a typical patched specimen. The patches were tapered across the thickness to reduce stress concentrations due to edge effects. Table 2 lists the layup and dimension for the boron patches. Layups one and four were obtained from work done for the Navy by Northrop. [3] The other patches were designed to be more orthotropic and perform in more general stress fields. Before the patches were bonded, the surface of the aluminum was treated with a phosphoric acid non-tank anodize (PANTA) as specified in Reference 4 and listed in Appendix I. AVCO 5521/4 boron epoxy was used to help control the induced bending stress problem due to differences in coefficients of thermal expansion. This system requires a 250°F cure as shown in Appendix 1 instead of the 350°F cure which the more commonly used

5505/4 system requires. When the lower (below 250°F) cure adhesives were used, the patches had to be precured before being bonded to the aluminum. This procedure is also listed in Appendix 1.

TABLE 2
Patch Layups and Dimensions

Patch Number	Patch Layup (in.)	Inner Diameter (in.)	Outer Diameter
1	$(0_2,90)_s$	1.94	2.14
2	$(\pm45,90,0)_s$	1.94	2.34
3	$(\pm45,90_2,0_2)_s$	1.94	2.34
4	$(\pm45,0_2,90,0_3)$	1.94	2.24
5	$(\pm45,0_2,90_2,0)_s$	1.94	2.54
6	$(0)_3$	1.94	1.94
7	$(0)_4$	1.94	1.94
8	$(0)_5$	1.94	1.94
9	$(0)_7$	1.94	2.34
10	$(0)_{12}$	1.94	2.34
11	$(0)_{16}$	1.94	2.54

Before bonding, the bottoms of the precured patches were sand-blasted and cleaned with acetone and then distilled water. The surface to be patched was treated with Micro-Measurement A1 Conditioner, a surface cleaner. This was placed on the surface for 10 minutes and then cleaned off with distilled water. Then the specimens and patch were held at 100°F for 1 hour to remove moisture. K138, a two-part adhesive, was first properly mixed, then applied in a thin, even bondline to the patch. The patch was then placed flush to the edge of the aluminum and centered over the crack. Weights were placed on the specimen to provide about 2 psi pressure. The weights were separated from the specimen with a layer of non-porous material to keep the adhesive off of the weights. The system was then heated to 100°F for 24 hours to cure the adhesive. Two sets of precracked specimens were sent to the Australian Aeronautical Research Laboratories, patched, and returned for testing. These specimens were repaired by three different methods, using three different adhesives chosen by ARL. Half of the first set were repaired by cocuring the patches in place with FM73 adhesive. These were cured at 176°F for 8 hours. The other half were repaired by bonding precured patches with the K138 adhesive. These were cured in place for 8 hours at 104°F. The final set was repaired with cocured patches using AF126 adhesive. These were cured at 150°F for 8 hours.

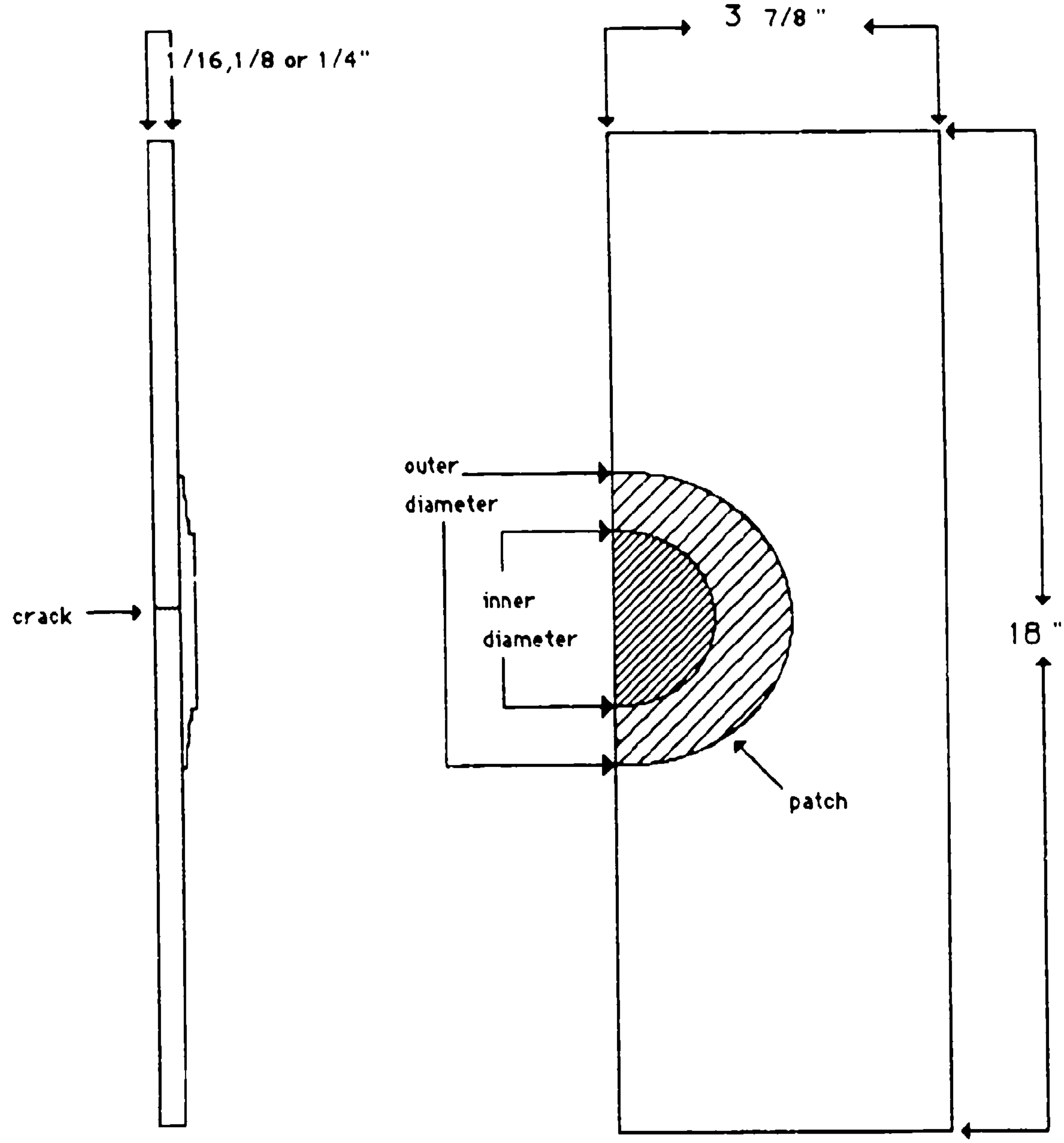

Figure 1. Typical Patched Specimen

SECTION IV

TESTING

Testing was done with several variables including room-temperature cure adhesives, high-temperature cure adhesives, metal thickness, single and double-sided patches, patches varying in layup, shapes, material, constant amplitude and flight spectrum loading, and some repairs done in Australia. Appendix II lists the specimens tested with their respective variables.

While most patches were single sided, a few were patched on both sides. In most cases, a single-sided patch is all that would be practical, since typical repairs do not allow easy access to both sides of the structure. However, with a thicker specimen, particularly the 1/4-inch specimens, the repairs were not extending the lifetime of the aluminum nearly as long as on the thinner specimens, owing to the stress variation across the thickness of the aluminum. Double-sided patches were then tried to see if this effect could be overcome.

Two different types of loading were used during the testing. The simpler loading was constant amplitude with an R ratio (minimum stress divided by maximum stress) of 0.1 and a maximum load of 20 KSI. The other loading is called Falstaff Flight Spectrum, an abbreviated version of the Falstaff Spectrum [2]. Figure 2 shows the loads seen by the specimen during one flight of the Falstaff Flight Spectrum. Maximum stress under this loading was 20 KSI and minimum load was -2.7 KSI. Guides were used on the specimens to prevent buckling during compression loads.

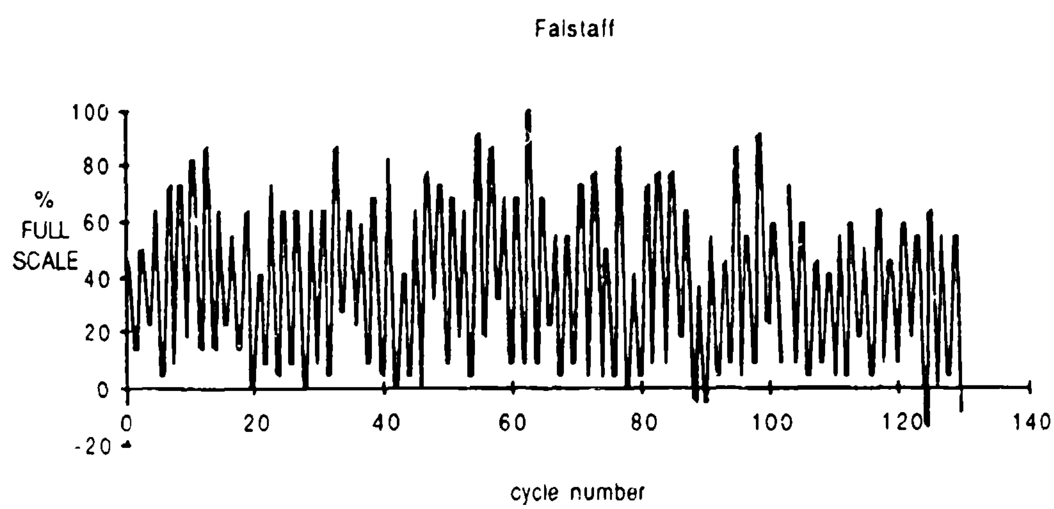

Figure 2. Falstaff Short Spectrum

Two major modes of failure were found during the tests. Figure 3 shows the patch failure mode. Here the patch fractures with the aluminum. The adhesive does not fail, except locally over the crack itself. Figure 4 shows the adhesive-type failure mode In most cases, the adhesive failed cohesively. The lower temperature cure adhesives provided some exceptions with the adhesive failing adhesively.

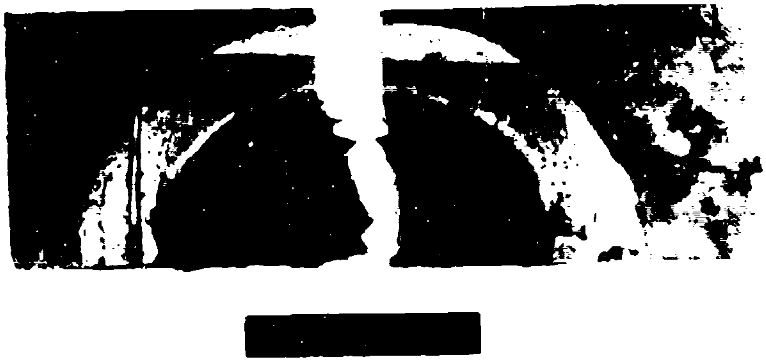

Figure 3. Patch Failure Mode

Figure 4. Adhesive Failure Mode

Baseline Panel Testing

The material for baseline panel testing was not cured under the normal 100 psi in order to simulate the way a patch would be applied under field conditions. Therefore we cured a small panel under the same conditions as the patches used in the repair (250°F and full vacuum pressure) to check some basic material properties. The patches on the aluminum carry loads through

tension and shear; therefore, 0° tensile, short beam shear and 0° flexural tests were examined for the panel testing.

A typical ply of the boron prepreg is composed of a single layer of boron fibers laid up on a scrim cloth and impregnated with epoxy. Some of the initial patches were laid up with scrim-to-scrim in some layers and boron-to-boron in other layers. There was a question whether this would have an effect on shear and flexural properties. Therefore, a second panel was laid up and cured. This panel started with an outer scrim layer, then two boron layers together, then two scrim layers together, and so on for the eight plies. The first panel was laid up with no adjacent boron or scrim layers. Both panels were bled the same and followed the same cure cycle as the patches. The results of the material test specimens are listed in Table 3. Only very small differences were noted between the two panels, indicating the placing of scrims together was not a major problem in this application.

Table 3
Material Property Tests

		Panel A	Panel B
A. Tensile Ultimate Load (KSI)		168	200
		221	213
		179	187
	Avg.	189	200
B. Short Beam Shear (KSI)		11.3	12.0
		12.1	10.8
		12.9	12.2
		10.1	10.9
		11.5	11.6
		10.4	9.7
	Avg.	11.4	11.2
C. Flexural Strength (KSI)		267	226
		287	272
		288	266
		303	261
		289	308
		279	287
	Avg.	285	270

D. Flexural Modulus (MSI)		21.5	20.9
		25.6	24.4
		26.1	22.5
		27.1	22.5
		24.9	26.4
		24.3	23.2
	Avg.	24.9	23.3

Panel A. 8 Ply with Alternate Scrims
Panel B. 8 Ply with Scrims Together

In order to confirm the existence of a difference between the crack length at the bond surface and at the opposite surface, one specimen had marker bands placed on the crack during the test. The marker bands were generated by cycling the specimen with the same maximum load but R=0.85 for enough cycles to add an additional 0.01 inch to the crack at 5-thousand-cycle intervals during the test. This creates a mark on the fracture surface which is different from the normal fracture and can easily be measured after the test is complete and the specimen is broken. X-ray and ultrasonic techniques were also tried in order to measure the crack length difference during the test, but were not accurate enough to measure the difference. Table 4 lists the measured data for a 1/8-inch-thick specimen patched with a rectangular patch of 5 plies of unidirectional boron. This confirms that the crack length on the nonpatched side is longer than the patched side. This explains why the single-sided patches are more effective on the thinner (1/16-inch) materials. With the thicker aluminum, particularly the 1/4-inch-thick specimens, the variation of the stress across the thickness of the metal is high, which renders the patch relatively ineffective.

Table 4
Crack Length Differences

Patched Side (in.)	Unpatched Side (in.)	Difference (in.)
.312	.407	.086
.455	.552	.097
.657	.753	.096
.913	1.013	.100
1.342	1.403	.060
2.007	2.065	.058
failed	failed	

SECTION V

RESULTS

An A versus N (crack length versus cycles) curve is shown in Figure 5. The initial cracks grown from the 0.050-inch notch varied in length, as can be seen in the figure. In order to compare the different patches, a common starting point must be found. This was done by shifting the various curves horizontally (along the X-axis) until the curves intercepted the Y-axis (crack length) at the desired point. Due to the nonlinearity of the A versus N curve, it is also best to have this reference point constant across specimens of equal thickness. When these curves were shifted along the X axis, the baseline enters the highly curved portion, while the repaired specimen A vs N curve was still in its flat, linear portion. A much larger percentage of the baseline specimens' life will be lost than will the repaired specimen. The starting point used for both 1/8-inch and 1/16-inch specimens was 0.34 inch. Once this point was established, we then compared the effectiveness of different patches by computing their lifetime extension.

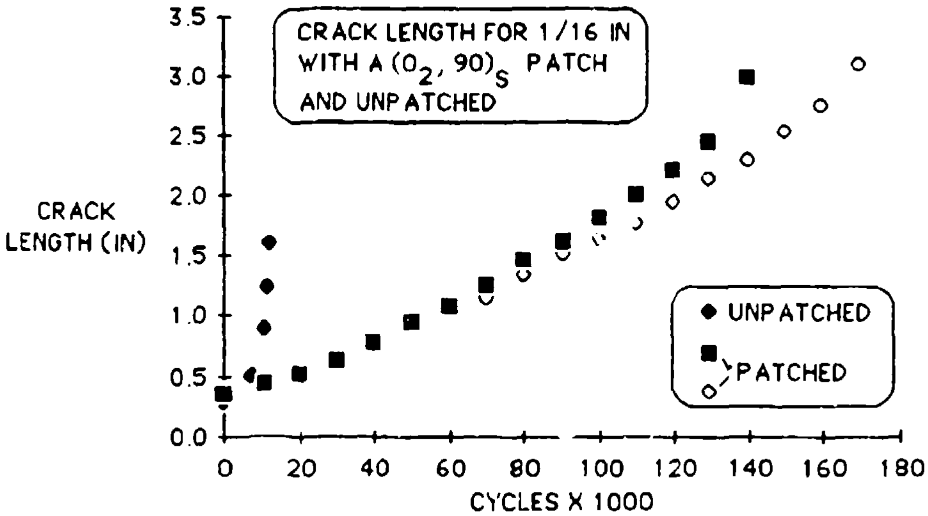

Figure 5. Typical Cycles vs. Crack Length

Figures 6 through 10 are summary bar graphs of life extension for different patches, aluminum thickness, and loading methods, as specified. The baseline specimen life (1/16-inch constant amplitude) was 7,065 cycles from a 0.34-inch crack to failure. Table 5 lists the baseline specimen lives for each thickness and loading type. As can be seen in Figure 6, most of the patches here performed well. The $(\pm45,90,0)_s$ patch was the worst, but still showed a life extension of 16.4 times. All other repairs in this group yielded life extension averages from 19 to 22 times the baseline life. The first four columns used AF163 adhesive cured at 250°F. Column 6 in this figure is of a single specimen repaired by the

Australian Aeronautical Research Laboratory (ARL) with a (0_4)patch and a 104°F cure adhesive, K138. This single specimen had a life extension of 22.1 times, which is as good as the average extension of the ($\pm45,90_2,0_2)_s$ patch. Two (0_4) repairs done by ARL shown in column 7 using AF126 at 250°F also performed well, with an average life extension of 19.6 times.

Table 5
Baseline Values

Constant Amplitude	Cycles
1/16 in.	7065
1/8 in.	3804
1/4 in.	1154
Falsataff Flights	**Flights**
1/16 in.	1033
1/8 in.	549
1/4 in.	289

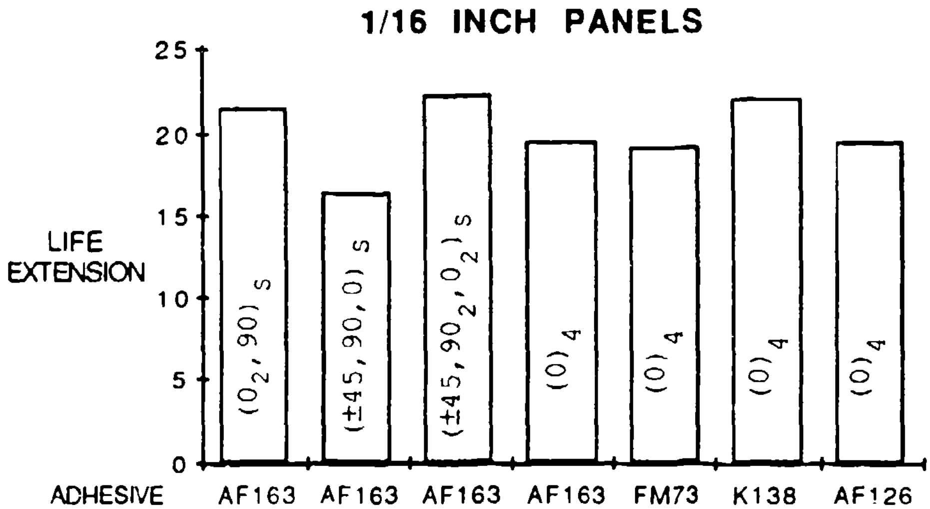

Figure 6. 1/16-Inch-Thick Constant Amplitude Tests

The differences in the patches were much more pronounced under the Falstaff Flight spectrum loading. As shown in Figure 7, the ($\pm45,90_2,0_2)_s$ patch clearly performed better than the others, yielding a life extension of 21.8 times. The life extension of unidirectional layups decreased significantly under the spectrum loading. The last two columns show data (0_3) and (0_5) patches, respectively. Even the (0_5) had a significantly lower life extension than the ($\pm45,90_2,0_2)_s$ patch, unlike the constant amplitude case where the (0_4) patches

had performed roughly equivalently to the $(\pm45,90_2,0_2)_s$ patch. The ARL repaired specimens in column four used AF126 cured at 250°F.

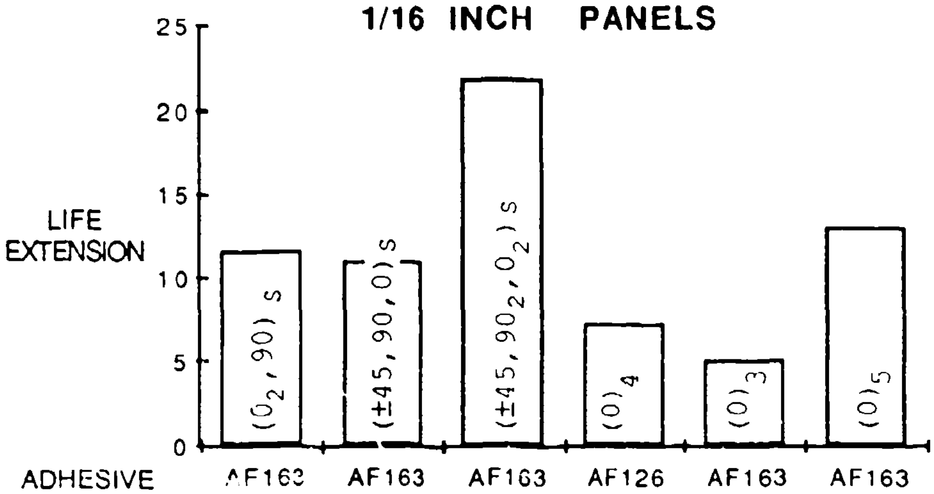

Figure 7. 1/16-Inch-Thick Spectrum Tests

Overall, the 1/8-inch specimens tested at constant amplitude and plotted in Figure 8 did not show quite as great a life extension as the 1/16-inch specimens. Here the (0_7) specimens repaired by the ARL using AF126 adhesive with a 250°F cure performed the best with a life extension of 17.7 times, nearly as good as the 1/16-inch specimens. However, the single ARL repaired (0_7) specimen using the K138 adhesive, 104°F cure showed a life extension of only 8.3 times. Recall that the K138 with a (0_4) patch on the 1/16 inch specimen with constant amplitude loading performed very well. The $(\pm45,0_2,90,0_3)$ specimen did a little better than the (0_7) K138 repaired specimen, and the $(\pm45,0_2,90_2,0)_s$ specimen had an average life extension of 11.4 times.

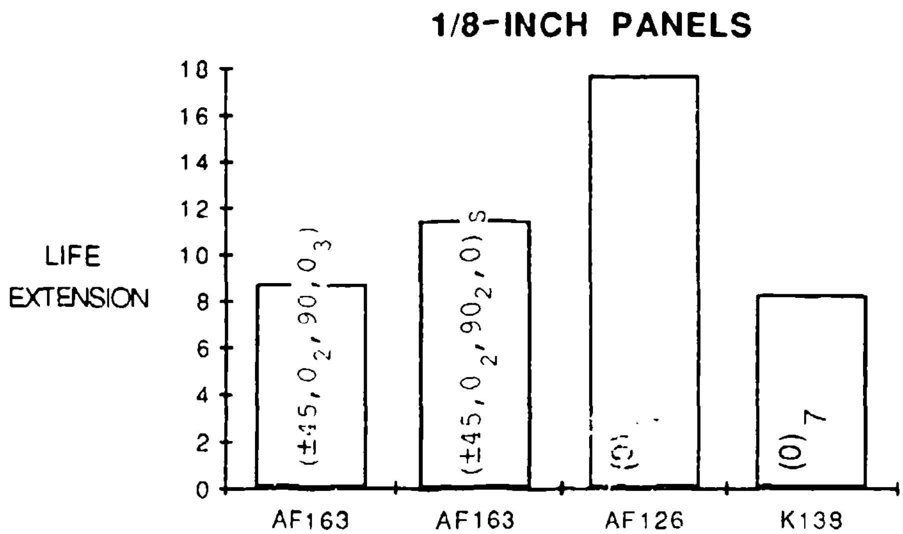

Figure 8. 1/8-Inch-Thick Constant Amplitude Tests

The Falstaff flight spectrum loading of the 1/8-inch specimens shown in Figure 9 again showed a large relative drop in life extension with the unidirectional patch repairs. The top-performing patch here was the $(\pm45,0_2,90_2,0)_s$ patch, with an average life extension of 7.3 times, while the ARL repaired (0_7) using the AF126 adhesive and 250°F cure had an average life extension of 6.3 times. Column 4 shows the results of a (0_7) patch repair using K138 adhesive, 104°F cure, and an alternate aluminum preparation method. Here the aluminum was sand-blasted, cleaned, and treated with Micro Measurement Conditioner A-1 instead of being etched with the PANTA process. The average life extension for these specimens was 4.8 times, very close to that of the single (0_7) specimen using AF163 and a 250°F cure (4.9 times). Still another (0_7) specimen, this time repaired by the ARL with a 176°F cure and FM73 adhesive, showed a life extension of 6.8 times.

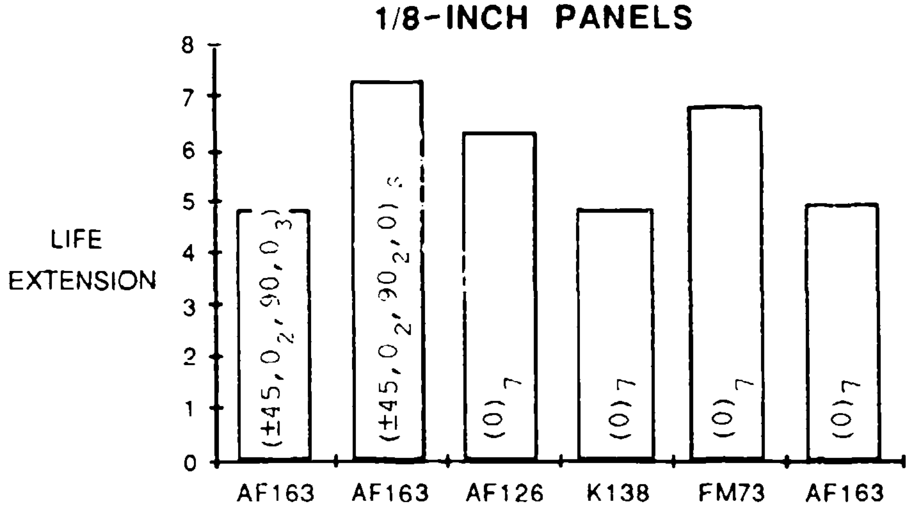

Figure 9. 1/8-Inch-Thick Spectrum Tests

Since the baseline lifetime of the 1/4-inch specimens was much shorter than the 1/8-inch or 1/16-inch specimens, direct comparisons between these different thickness specimens cannot be made. Using a 0.26-inch crack as the starting point for comparison, a (0_{12}) patch under constant amplitude loading had an average life extension of 15.8 times (see Figure 10). Under Falstaff flight loading, a (0_{12}) specimen showed a life extension of 4.8 times, while a (0_{16}) specimen showed an extension of 6.3 times. All of the above specimens used a PANTA aluminum preparation and AF163 adhesive with a 250°F cure.

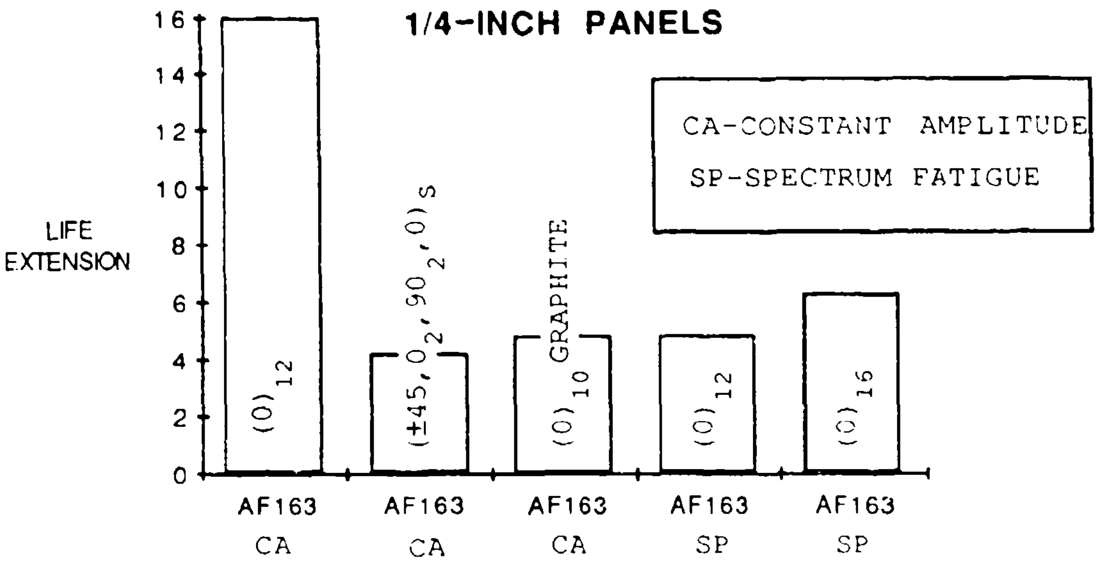

Figure 10. 1/4-Inch-Thick Specimens

The repairs done using patches on both sides of the cracked specimen were extremely effective. Although crack lengths could not be monitored while the specimen was being tested without removing it from the test machine, the three double-sided 1/8-inch specimens and the one 1/4-inch specimen all cycled well past the best of the single side repaired specimens. For example, the 1/8-inch specimens ranged from a low of 288,000 constant amplitude cycles to a high of 1,244,000 cycles, but all these specimens failed outside the patched area. The 1/4-inch double-sided specimen cycled for 178,000 cycles. Figure 11 shows these results.

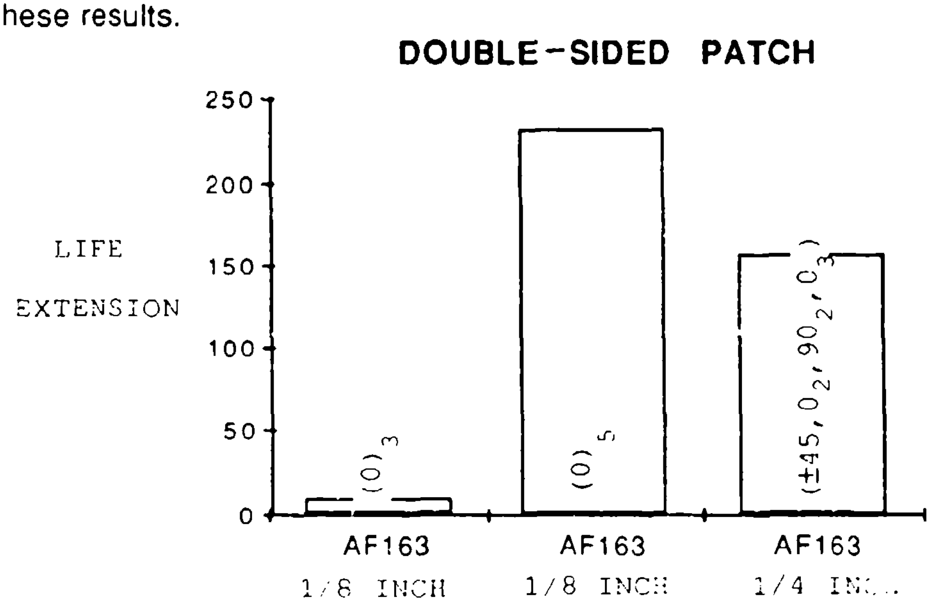

Figure 11. Results of Double Sided Patches

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

Overall, the patches were very effective in slowing down crack growth in the repaired specimens, particularly the thinner material (1/16-inch aluminum). The variations of the stresses across the metal seem to limit the effectiveness in the thicker specimens. The patches having more balance between 0°, 45°, and 90° plies performed better under the Falstaff flight spectrum loading, including compression, than did unidirectional patches. The $(\pm45,90_2,0_2)_s$ was the best performing patch for 1/16-inch-thick aluminum, as was the $(\pm45,0_2,90_2,0)_s$ patch for 1/8 inch aluminum. The low-temperature (104°F) curing adhesive, K138, performed very well in some circumstances, but lacked the consistency of the 250° F curing adhesives. This may have been due to the fact that the K138 is more difficult to apply correctly than the other adhesives because it is a two-part adhesive, whereas the higher temperature adhesives are carrier cloth-type adhesives which are easy to get the required even thickness distribution across the adherends

The results of this program have application at a depot level where controlled surface treatments can be completed, regulated heating is available, and special techniques can be used to apply the required pressure for a proper cure. In a remote field location or in a rapid battle-damage situation, equipment for this type of bonding will probably not be available. The potential exists to do this type of repair using room temperature cure systems in wet layups with graphite or fiber-glass cloth. Further work needs to be done in this area.

REFERENCES

1. Baker, A. A., "Work on Application of Advanced Composites at The Aeronautical Research Laboratories," Composites 9 (1), 1978.

2. van Dijk, G. M. and de Jonge, J. B., Introduction to a Fighter Aircraft Loading Standard for Fatigue Evaluation - FALSTAFF, National Aerospace Laboratory, The Netherlands, NLR MP 75017, May 1975.

3. Ratwani, M. M., and Labor, J. D., "Composite Patches For Metal Structure," Navy Contract N62269-79-C-0271, May 1979.

4. "Adhesive Bonded Aerospace Structures Standarized Repair Handbook," Mil-hdbk-337, 1983.

APPENDIX I
FABRICATION PROCEDURES

Before the patches were bonded, the surface of the aluminum was treated with a phosphoric acid non-tank anodize (PANTA) as specified in Reference 4. The following steps were used:

(1) Solvent-wipe with MEK

(2) Abrade with nylon abrasive pads

(3) Dry wipe with clean gauze

(4) Apply a uniform coat of gelled 12% phosphoric acid

(5) Place three layers of gauze and apply enough gelled phosphoric acid to completely saturate a piece of stainless steel screen over the coating. Apply another coating of gelled phosphoric acid

(7) Connect the screen as a cathode (-) and the aluminum as an anode (+) for a D.C. power source

(8) Supply a potential of 6 volts for 10 minutes

(9) Remove screen and gauze

(10) Moisten clean gauze with water and lightly wipe off the remaining gelled acid. Rinse the surface with water within 5 minutes

(11) Force air oven dry for 30 minutes at 150°F

(12) Examine the surface with a polarized filter rotated 90° at a low angle of incidence to the specimen. A properly anodized surface will show an interference color

(13) Repeat 4 through 12 if no color

(14) Coat anodized area with American Cyanimid's BR127 primer

(15) Wrap in Kraft paper until need for patching

AVCO 5521/4 boron epoxy was used to help control the induced bending stress problem due to differences in coefficients of thermal expansion. This system requires a 250°F cure instead of the 350°F cure which the more commonly used 5505/4 system requires.

The following procedure was followed in patching the precracked specimens:

(1) Add one layer of AF163 to the bottom of the patch

(2) Center the patch over the cracked area of the specimen

(3) Place a layer of non-porous material over the patch

(4) Place 2 layers of glass vent cloth over the non-porous and extend to a vacuum port

(5) Place a vacuum bag over the patching area and draw a minimum of 28 in-Hg

(6) Heat the specimen to 250°F at 5°F per minute with a heat blanket or heated platen

(7) Hold at 250°F for 2 hours

(8) Allow to cool to less than 140°F before removing vacuum

(9) Ultrasonically inspect specimens for disbonds

When the lower (below 250°F) cure adhesives were used, the patches had to be precured before being bonded to the aluminum. The precured patches were laid up individually and cured as follows:

(1) Place a layer of non-porous material over the patch.

(2) Place two layers of glass vent cloth over the non-porous and extend to a vacuum port.

(3) Draw a minimum of 28 in-Hg vacuum.

(4) Heat to 250°F at 5°F per minute.

(5) Apply 85 psi pressure.

(6) Hold at 250°F for 2 hours.

(7) Allow to cool to less than 140°F before removing vacuum.

(8) Ultrasonically inspect specimens.

APPENDIX II

TEST SPECIMEN LIST

SPECIMEN # 1 THICKNESS 1/16
LAYUP BASELINE
PATCH SHAPE NONE
CURE SYSTEM NONE
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .000
FAILURE CYCLES 37100
FAILURE MODE ALUMINUM FATIGUE

SPECIMEN # 2 THICKNESS 1/16
LAYUP (0/0/-45/45/0/0)
PATCH SHAPE SEMICIRCLE
CURE SYSTEM COCURE 250 F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .303
FAILURE CYCLES 138000
FAILURE MODE ALUMINUM AND BORON FATIGUE

SPECIMEN # 3 THICKNESS 1/16
LAYUP (45/-45/90/0)S
PATCH SHAPE SEMICIRCLE
CURE SYSTEM COCURE 250F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .300
FAILURE CYCLES 130600
FAILURE MODE COHESIVE BOND

SPECIMEN # 4 THICKNESS 1/16
LAYUP (0/0/90)S
PATCH SHAPE SEMICIRCLE
CURE SYSTEM COCURE 250 F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .323
FAILURE CYCLES 149000
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 5 THICKNESS 1/16
LAYUP (45/-45/90/0)S
PATCH SHAPE SEMICIRCLE
CURE SYSTEM COCURED 250 F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .308
FAILURE CYCLES 112000
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 6 THICKNESS 1/16
LAYUP (45/-45/90/90/0/0)S
PATCH SHAPE SEMICIRCLE
CURE SYSTEM COCURE 250 F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .492
FAILURE CYCLES 131000
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 7 THICKNESS 1/16
LAYUP (45/-45/90/90/0/0)S
PATCH SHAPE RECTANGLE
CURE SYSTEM COCURE 250 F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .298
FAILURE CYCLES 173000
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 8 THICKNESS 1/16
LAYUP (0/0/90)
PATCH SHAPE RECTANGULAR
CURE SYSTEM COCURE 250 F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .303
FAILURE CYCLES 225000
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 9 THICKNESS 1/16
LAYUP (0/0)
PATCH SHAPE RECTANGULAR
CURE SYSTEM COCURE 250 F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .304
FAILURE CYCLES 97000
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 10 THICKNESS 1/16
LAYUP (45/-45/90/0)S
PATCH SHAPE RECTANGULAR
CURE SYSTEM COCURE 250 F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .301
FAILURE CYCLES 128000
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 11 THICKNESS 1/16
LAYUP (0/0/90)S
PATCH SHAPE SEMICIRCLE
CURE SYSTEM COCURE 250 F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .285
FAILURE CYCLES 170000
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 12 THICKNESS 1/16
LAYUP (45/-45/90/90/0/0)S
PATCH SHAPE SEMICIRCLE
CURE SYSTEM COCURE 250 F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .314
FAILURE CYCLES 160000
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN #	13	THICKNESS	1/16
LAYUP (0)S			
PATCH SHAPE	RECTANGULAR (1/2 WIDTH)		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.260		
FAILURE CYCLES	140000		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN #	14	THICKNESS	1/16
LAYUP BASELINE			
PATCH SHAPE	NONE		
CURE SYSTEM	NONE		
TEST TYPE	SPECTRUM	TEST LEVEL	35000
INITIAL CRACK LENGTH	.129		
FAILURE CYCLES	150		
FAILURE MODE	ALUMINUM FATIGUE		

SPECIMEN #	15	THICKNESS	1/16
LAYUP BASELINE			
PATCH SHAPE	NONE		
CURE SYSTEM	NONE		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.137		
FAILURE CYCLES	2274		
FAILURE MODE	ALUMINUM FATIGUE		

SPECIMEN #	16	THICKNESS	1/16
LAYUP BASELINE			
PATCH SHAPE	NONE		
CURE SYSTEM	NONE		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.130		
FAILURE CYCLES	1921		
FAILURE MODE	ALUMINUM FATIGUE		

SPECIMEN #	17	THICKNESS	1/16
LAYUP (45/-45/90/90/0/0)S			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 250F		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.258		
FAILURE CYCLES	16954		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN #	18	THICKNESS	1/16
LAYUP (45/-45/90/0)S			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.300		
FAILURE CYCLES	9258		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN #	19	THICKNESS	1/8
LAYUP BASELINE			
PATCH SHAPE	NONE		
CURE SYSTEM	NONE		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.033		
FAILURE CYCLES	39919		
FAILURE MODE	ALUMINUM FATIGUE		

SPECIMEN #	20	THICKNESS	1/8
LAYUP (45/-45/0/0/90/0/0/0)			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 250F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.512		
FAILURE CYCLES	30000		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN #	21	THICKNESS	1/8
LAYUP (45/-45/0/0/90/90/0)S			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.303		
FAILURE CYCLES	52000		
FAILURE MODE	ALUMINUM FATIGUE AND COHESIVE BOND		

SPECIMEN #	22	THICKNESS	1/8
LAYUP (45/-45/0/0/90/0/0/0)			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.297		
FAILURE CYCLES	35000		
FAILURE MODE	COHESIVE BOND		

SPECIMEN #	23	THICKNESS	1/8
LAYUP (45/-45/0/0/90/90/0)S			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.326		
FAILURE CYCLES	40000		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN #	24	THICKNESS	1/8
LAYUP (45/-45/0/0/90/0/0/0)			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.307		
FAILURE CYCLES	35437		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN #	25	THICKNESS	1/8
LAYUP	(0)5 REC 1/2 WIDTH DOUBLE SIDED		
PATCH SHAPE	RECTANGULAR		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.317		
FAILURE CYCLES	288000		
FAILURE MODE	ALUMINUM FATIGUE OUTSIDE PATCH		

SPECIMEN #	26	THICKNESS	1/8
LAYUP	(0)5 DOUBLE SIDED		
PATCH SHAPE	RECTANGULAR		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.308		
FAILURE CYCLES	506000		
FAILURE MODE	ALUMINUM FATIGUE OUTSIDE PATCH		

SPECIMEN #	27	THICKNESS	1/8
LAYUP	(0)5 DOUBLE SIDED		
PATCH SHAPE	RECTANGULAR		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.312		
FAILURE CYCLES	1244000		
FAILURE MODE	ALUMINUM FATIGUE OUTSIDE PATCH		

SPECIMEN #	28	THICKNESS	1/8
LAYUP	(0)3 DOUBLE SIDED		
PATCH SHAPE	RECTANGULAR		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.434		
FAILURE CYCLES	20493		
FAILURE MODE	ALUMINUM FATIGUE OUTSIDE PATCH		

SPECIMEN #	29	THICKNESS	1/8
LAYUP	BASELINE		
PATCH SHAPE	NONE		
CURE SYSTEM	NONE		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.000		
FAILURE CYCLES	1413		
FAILURE MODE	ALUMINUM FATIGUE		

SPECIMEN #	30	THICKNESS	1/8
LAYUP	BASELINE		
PATCH SHAPE	NONE		
CURE SYSTEM	NONE		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.000		
FAILURE CYCLES	1230		
FAILURE MODE	ALUMINUM FATIGUE		

SPECIMEN # 31 THICKNESS 1/4
LAYUP BASELINE
PATCH SHAPE NONE
CURE SYSTEM NONE
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .000
FAILURE CYCLES 20000
FAILURE MODE ALUMINUM FATIGUE

SPECIMEN # 32 THICKNESS 1/4
LAYUP (45/-45/0/0/90/90/0)S
PATCH SHAPE SEMICIRCLE
CURE SYSTEM COCURE 250 F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .318
FAILURE CYCLES 5000
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 33 THICKNESS 1/4
LAYUP (45/-45/0/0/90/0/0/0)DOUBLE SIDED
PATCH SHAPE RECTANGULAR
CURE SYSTEM COCURE 250 F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .280
FAILURE CYCLES 178000
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 34 THICKNESS 1/16
LAYUP (0/0/90)S
PATCH SHAPE SEMICIRCLE
CURE SYSTEM COCURE 250 F
TEST TYPE SPECTRUM TEST LEVEL 20000
INITIAL CRACK LENGTH .298
FAILURE CYCLES 9308
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 35 THICKNESS 1/8
LAYUP (0)S
PATCH SHAPE SEMICIRCLE
CURE SYSTEM COCURE 250F
TEST TYPE SPECTRUM TEST LEVEL 20000
INITIAL CRACK LENGTH .335
FAILURE CYCLES 2513
FAILURE MODE 50%COHESIVE/ 50%ADHESIVE

SPECIMEN # 36 THICKNESS 1/8
LAYUP (0)S GRAPHITE
PATCH SHAPE SEMICIRCLE
CURE SYSTEM COCURE 350 F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .267
FAILURE CYCLES 30000
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 37 THICKNESS 1/8
LAYUP (45/-45/0/0/90/90/0)S
PATCH SHAPE SEMICIRCLE
CURE SYSTEM CICURE 250 F
TEST TYPE SPECTRUM TEST LEVEL 20000
INITIAL CRACK LENGTH .317
FAILURE CYCLES 4166
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 38 THICKNESS 1/4
LAYUP (0)10 GRAPHITE
PATCH SHAPE SEMICIRCLE
CURE SYSTEM COCURE 350 F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .400
FAILURE CYCLES 5000
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 39 THICKNESS 1/8
LAYUP (45/-45/0/0/90/0/0/0)
PATCH SHAPE SEMICIRCLE
CURE SYSTEM COCURE 250 F
TEST TYPE SPECTRUM TEST LEVEL 20000
INITIAL CRACK LENGTH .319
FAILURE CYCLES 3012
FAILURE MODE COHESIVE BOND

SPECIMEN # 40 THICKNESS 1/16
LAYUP (0)4 AUSTRALIAN
PATCH SHAPE SEMICIRCLE
CURE SYSTEM PRECURED 104 F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .314
FAILURE CYCLES 219000
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 41 THICKNESS 1/8
LAYUP (0)7 AUSTRALIAN
PATCH SHAPE SEMICIRCLE
CURE SYSTEM PRECURED 104 F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .304
FAILURE CYCLES 36000
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 42 THICKNESS 1/8
LAYUP (0)7 AUSTRALIAN
PATCH SHAPE SEMICIRCLE
CURE SYSTEM COCURE 176 F
TEST TYPE SINE TEST LEVEL 20000
INITIAL CRACK LENGTH .493
FAILURE CYCLES 31000
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN #	43	THICKNESS	1/16
LAYUP (0)4 AUSTRALIAN			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURED 176 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.688		
FAILURE CYCLES	99132		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN #	44	THICKNESS	1/16
LAYUP (0)4 AUSTRALIAN			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 176 F		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.389		
FAILURE CYCLES	7700		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN #	45	THICKNESS	1/8
LAYUP (0)7 AUSTRALIAN			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 176 F		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.332		
FAILURE CYCLES	3637		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN #	46	THICKNESS	1/8
LAYUP (0)7 AUSTRALIAN			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	PRECURED 104 F		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.407		
FAILURE CYCLES	4711		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN #	47	THICKNESS	1/16
LAYUP (0)4			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.327		
FAILURE CYCLES	142000		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN #	48	THICKNESS	1/8
LAYUP (0)8			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.355		
FAILURE CYCLES	40208		
FAILURE MODE	COHESIVE BOND		

SPECIMEN #	49	THICKNESS	1/16
LAYUP (45/-45/0/0)			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	PRECURED		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.327		
FAILURE CYCLES	155000		
FAILURE MODE	COHESIVE BOND		

SPECIMEN #	50	THICKNESS	1/8
LAYUP (0)8			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	PRECURED		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.000		
FAILURE CYCLES	21314		
FAILURE MODE	COHESIVE BOND (SPECIMEN NOTCHED AT 11425 FLIGH		

SPECIMEN #	51	THICKNESS	1/8
LAYUP (45/-45/0/0/90/90/0)S			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.280		
FAILURE CYCLES	4102		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN #	52	THICKNESS	1/8
LAYUP (45/-45/0/0/90/0/0/0)			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.295		
FAILURE CYCLES	3089		
FAILURE MODE	COHESIVE BOND		

SPECIMEN #	53	THICKNESS	1/8
LAYUP (0)7			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.303		
FAILURE CYCLES	2790		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN #	54	THICKNESS	1/16
LAYUP (45/-45/90/90/0/0)S			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.248		
FAILURE CYCLES	19764		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN # 55 THICKNESS 1/16
LAYUP (45/-45/90/0)S
PATCH SHAPE SEMICIRCLE
CURE SYSTEM COCURE 250 F
TEST TYPE SPECTRUM TEST LEVEL 20000
INITIAL CRACK LENGTH .280
FAILURE CYCLES 9079
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 56 THICKNESS 1/16
LAYUP (0/0/90)S
PATCH SHAPE SEMICIRCLE
CURE SYSTEM COCURE 250 F
TEST TYPE SPECTRUM TEST LEVEL 20000
INITIAL CRACK LENGTH .280
FAILURE CYCLES 9768
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN # 57 THICKNESS 1/8
LAYUP (0)7
PATCH SHAPE SEMICIRCLE
CURE SYSTEM PRECURED 105 F
TEST TYPE SPECTRUM TEST LEVEL 20000
INITIAL CRACK LENGTH .270
FAILURE CYCLES 3611
FAILURE MODE COHESIVE BOND

SPECIMEN # 58 THICKNESS 1/16
LAYUP (0)5
PATCH SHAPE SEMICIRCLE
CURE SYSTEM PRECURED 105 F
TEST TYPE SPECTRUM TEST LEVEL 20000
INITIAL CRACK LENGTH .244
FAILURE CYCLES 17216
FAILURE MODE COHESIVE BOND

SPECIMEN # 59 THICKNESS 1/16
LAYUP (0)3
PATCH SHAPE SEMICIRCLE
CURE SYSTEM PRECURED 105 F
TEST TYPE SPECTRUM TEST LEVEL 20000
INITIAL CRACK LENGTH .273
FAILURE CYCLES 6114
FAILURE MODE NOT FAILED

SPECIMEN # 60 THICKNESS 1/16
LAYUP (0)4 AUSTRALIAN
PATCH SHAPE SEMICIRCLE
CURE SYSTEM COCURED 150 F
TEST TYPE SPECTRUM TEST LEVEL 20000
INITIAL CRACK LENGTH .323
FAILURE CYCLES 6114
FAILURE MODE BORON AND ALUMINUM FATIGUE

SPECIMEN #	61	THICKNESS	1/16
LAYUP (0)4 AUSTRALIAN			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 150 F		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.240		
FAILURE CYCLES	6720		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN #	62	THICKNESS	1/8
LAYUP (0)7 AUSTRALIAN			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 150 F		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.257		
FAILURE CYCLES	4418		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN #	63	THICKNESS	1/8
LAYUP (0)7 AUSTRALIAN			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 150 F		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.315		
FAILURE CYCLES	2856		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN #	64	THICKNESS	1/16
LAYUP (0)4 AUSTRALIAN			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 150 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.338		
FAILURE CYCLES	162950		
FAILURE MODE	BORON AND ALUMINUM FATIGUE		

SPECIMEN #	65	THICKNESS	1/16
LAYUP (0)4 AUSTRALIAN			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 150 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.202		
FAILURE CYCLES	173360		
FAILURE MODE	COHESIVE BOND		

SPECIMEN #	66	THICKNESS	1/8
LAYUP (0)7 AUSTRALIAN			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 150 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.287		
FAILURE CYCLES	84111		
FAILURE MODE	COHESIVE BOND		

SPECIMEN #	67	THICKNESS	1/8
LAYUP (Ø)7 AUSTRALIAN			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 150 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.282		
FAILURE CYCLES	91480		
FAILURE MODE	COHESIVE BOND		

SPECIMEN #	68	THICKNESS	1/4
LAYUP BASELINE			
PATCH SHAPE	NONE		
CURE SYSTEM	NONE		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.195		
FAILURE CYCLES	455		
FAILURE MODE	ALUMINUM FATIGUE		

SPECIMEN #	69	THICKNESS	1/4
LAYUP (Ø)12			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.193		
FAILURE CYCLES	18511		
FAILURE MODE	COHESIVE BOND		

SPECIMEN #	70	THICKNESS	1/4
LAYUP (Ø)12			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SINE	TEST LEVEL	20000
INITIAL CRACK LENGTH	.203		
FAILURE CYCLES	18210		
FAILURE MODE	COHESIVE BOND		

SPECIMEN #	71	THICKNESS	1/4
LAYUP (Ø)12			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.252		
FAILURE CYCLES	1415		
FAILURE MODE	COHESIVE BOND		

SPECIMEN #	72	THICKNESS	1/4
LAYUP (Ø)16			
PATCH SHAPE	SEMICIRCLE		
CURE SYSTEM	COCURE 250 F		
TEST TYPE	SPECTRUM	TEST LEVEL	20000
INITIAL CRACK LENGTH	.192		
FAILURE CYCLES	1861		
FAILURE MODE	COHESIVE BOND		

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